

EXECUTIVE SUMMARY

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The Astrotech 21 Optical Systems Technology Workshop was held in Pasadena, California on March 6 - 8, 1991. The purpose of the workshop was to examine the state of Optical Systems Technology at the National Aeronautics Space Administration (NASA), and in industry and academia, in view of the potential Astrophysics mission set currently being considered for the late 1990s through the first quarter of the 21st century. The principal result of the workshop is this publication, which contains an assessment of the current state of the technology, and specific

technology advances in six critical areas of optics, all necessary for the mission set.

The workshop was divided into six panels, each of about a dozen experts in specific fields, representing NASA, industry, and academia. In addition, each panel contained expertise that spanned the spectrum from x-ray to submillimeter wavelengths. The workshop was chaired by J. B. Breckinridge of the Jet Propulsion Laboratory (JPL), California Institute of Technology (Caltech). The six technology panels and their chairs were:

1. Wavefront Sensing, Control, and Pointing	Thomas Pitts	Itek Optical Systems, a Division of Litton
2. Fabrication	Roger Angel	Steward Observatory, University of Arizona
3. Materials and Structures	Theodore Saito	Lawrence Livermore National Laboratory
4. Optical Testing	James Wyant	WYKO Corporation
5. Optical Systems Integrated Modeling	Robert R. Shannon	Optical Sciences Center, University of Arizona
6. Advanced Optical Instruments Technology	Michael Shao	Jet Propulsion Laboratory, California Institute of Technology

This Executive Summary contains the principal recommendations of each panel.

1. Wavefront Sensing, Control, and Pointing

The Wavefront Sensing, Control, and Pointing panel defined six technology thrusts needed to support the mission set: active optics, active interferometry, pointing and attitude sensing and control, laser metrology, structures control, and system control architecture.

Active Optics is required to initialize and maintain optical elements in the optimal positions, orientations, and shapes to enable diffraction-limited performance and performance robustness. This will be especially critical for missions with large apertures

or baselines. Figure and wavefront sensors will be needed to measure the quality of the wavefront at a representative location in the optical train in order to provide appropriate error signals to a wavefront control system. Deformable mirrors (or their segmented equivalents) will be needed to correct the wavefront errors introduced by motions and deformations of the optics and support structure. For positioning and aligning optical elements on orbit, space-flyable precision positioning actuators are needed.

Active Interferometry is required for future interferometric missions. Like active optics, the phase of this sampled wavefront must be sensed, and its phase adjusted, in order that the lights from the individual apertures are combined coherently. Three

key areas for development within active interferometry require development are wavefront sensing, optical path length control, and beam combination. The first area, *wavefront sensing*, develops robust two-element systems for space qualification, high-rate fast-readout detectors, and efficient sensing architectures. The second area, *optical pathlength control*, focuses on delay line systems and metrology. The third area, *beam combination*, concentrates on the development of space-qualified systems that are consistent with the measurement goals, the wavefront sensing architecture, and space environment. The development of beam combiners that use interferometric cancellation of stray light to enable direct imaging of such high dynamic range objects, such as star-planet systems, is also a goal.

Pointing and Attitude Sensing and Control requirements for future astrophysics missions range widely and a variety of technologies must be brought to bear to address them. This development program is partitioned between pointing and attitude sensing and pointing and attitude control technologies. The first half of the program, *pointing and attitude sensing*, focuses on star trackers, fine guidance sensors, attitude transfer devices, and inertial attitude sensors. This program recommends the development of autonomous star trackers with an accuracy of better than 0.1 arcsec, the continued development of cryogenic visible fine guidance sensors along with an accurate star catalog in the UV/VIS/IR, the development of attitude transfer devices with nanoradian accuracy and very low thermal and radiation leakage, and the development of gyros capable of better than 0.0001 arcsec bias stabilities and lifetimes of greater than 15 years. The second half of the program, *pointing and attitude control*, concentrates on the development of actuators and fine pointing mirrors. An improvement of two orders of magnitude in torque capability and momentum capacity, with a simultaneous improvement of at least one order of magnitude in quietness along with high repeatability, is recommended for actuators. Fine-pointing mirror development should concentrate on the development

of highly compensated (i.e., better than 99% in all degrees of freedom) steering mirrors assemblies with projected centers of rotation. It should also produce technology for cryogenically cooled mirrors needed for missions in the IR.

Laser Metrology development is divided into four areas: laser sources, fiducial references, active components, and innovative metrology architectures. For *laser sources*, frequency stability is a critical property in almost all applications. For the near term astrometry missions, the development of a frequency stability of $\sim 10^{-10}$ is recommended. There is also an immediate need for the development of a suitable stabilization scheme for solid-state lasers, and their packaging into a low mass, low power package for space qualification. Additionally, development is needed in the areas of tunable lasers (with precision tuning and high stability) and low mass beam launcher manifold designs. The program in *fiducial reference* development stresses concept development and manufacturing process technology to improve the properties of acceptance angle and pathlength invariance (to over 120 deg and 1 nm, respectively) for applications in optical truss structures. Fiducial references for mirrors are also needed. Additionally, *active components* such as Bragg or Pockels cells will need development along with new approaches and new design tools for *innovative metrology architectures*.

A comprehensive *Structures-Control* technology program is recommended, with development efforts in six areas: vibration isolation systems, damping augmentation methods, control structure interaction (CSI), modal control, smart structures, and integrated structures-control design optimization. *Vibration isolation systems* are needed to isolate the structure from disturbance sources and the optics from the structure. Advances are needed in performance and low temperature operation. New techniques in *damping augmentation methods* are needed to lower vibration levels due to persistent disturbances and to hasten settling after transient excitations. Improvements are needed in performance and temperature ranges. Moreover,

developments are needed to enable operation in the radiation environment of space for long periods and to practicable methods of design and the identification of appropriate control architectures for the class of problems of interest to the optical community be supported. Furthermore, it is recommended that this work include the development of relevant system testbeds to serve as proving grounds for the technology. *Modal control* research is recommended on controlled structure system identification, self-tuning structural control, and systematic robust controller design. Additionally, it is recommended that reliable, flight-qualifiable components be developed, and that the system concept be demonstrated within a realistic testbed (*smart structures*) along with the development of a practical design tool for integrated optimization of the structure, control system, and optics (*integrated structure-control design optimization*).

System Control Architecture addresses the unprecedented dimensional complexity of spaceborne active optics and structures. New control theory and algorithm types will be needed to cope with the challenges. In particular, fundamental but highly focused research on systematic design and analysis methods, adaptive control, system identification, robust control, multiobjective optimal control and control of high dimensional systems are needed. Methods of suppressing optics control system interactions need to be developed along with the development of massively parallel architectures, algorithms, and hardware. Development of general tools (e.g., such as Matrix_x or the Matlab Control System toolbox) for design, analysis, and simulation of optical system control elements are necessary. Finally, research in optimal design, leading to multiloop optics control system design optimization techniques, is recommended. Specific problems in need of attention include simultaneous optics and control design optimization, minimum time figure and alignment initialization, and wavefront error minimizing figure and alignment maintenance.

2. Fabrication

The Fabrication panel made technology development recommendations in six areas: replicated optics, figuring large optics to 1 nm rms, lightweight cryogenic aspheric mirrors, systems issues in optical fabrication, innovative techniques, and facility needs and development.

Replicated Optics are required for both x-ray and submillimeter missions. Six critical developments are needed. X-ray applications require advancements in automated cylinder polishing, improvement in mandrel materials and lifetimes, and improved speed in cylinder production. Essential to the submillimeter missions are large, smooth, accurate composite face sheets that are supported on a lightweight sandwich construction. Once the surface quality can be met at ambient temperature, the technology will need to be pushed to the cryogenic regime required by submillimeter telescopes (80 K) since it will be necessary for the telescope panels (≈ 2 m) to maintain their qualities at operational temperature. To support the very large submillimeter missions in the latter part of the Astrotech period, panel areal densities of less than 5 kg/m² will also be needed.

Figuring Large Optics to 1 nm rms accuracy represents the most challenging item for optical fabrication. Once a stable substrate has been provided, and suitable in process testing has been defined, there remains the task of bringing the surface to the correct figure. At scales of less than 1 cm, development is needed of smoothing processes for large aspheric surfaces that will give the desired control of microroughness and small scale figure at the 1 nm level. At scales of 1 cm to tens of cm, development is needed of non-contact methods such as ion beam polishing for correction at the 1 nm level. At scales larger than tens of cm, active control techniques of the mirror will be required.

Developments will also be required in precision generation of large lightweight blanks.

The manufacture of *Lightweight Cryogenic Aspheric Mirrors* (with diameters of 4 m or larger) figured to 2 to 3 nm, which preserve their figure and radius of curvature to a temperature of 80 K, is a critical step in technology development required by several missions. Key developments include blank materials with effective coefficients of thermal expansions (CTEs) of zero at 80 K, lightweighting, gravity release compensation, active figure control, polishing, non-contact figuring, in-process testing, and the development of cryogenic testing facilities.

Systems Issues in Optical Fabrication were also addressed. Most of these issues were explored in more depth in other panels, but areas of significant overlap, where system decisions have the greatest impact on the fabrication process and cost, include smart structures, on-orbit alignment, figure control, rigidity scales, segment fabrication, and mounting considerations.

Innovative Techniques covered basic research and development activities in the early stages of development that offer potential. These topics include advanced techniques for monitoring and measuring material removal, continuously adaptive thin film and membrane optical systems, high throughput optics for high energy astronomy, prototype fabrication of innovative optical designs for high energy astronomy, advanced techniques for refractive optics including binary optics, and advanced techniques to reduce the number of fabrication and metrology cycles (manufacturing determinism).

In addition to the technology activities previously discussed, *Facility Needs and Development* of appropriate education programs were also recommended.

3. Materials and Structures

The Materials and Structures panel made technology recommendations in five specific areas:

vacuum coatings, materials science and engineering, environmental protection, reflector substrates, and structures.

The *Vacuum Coatings* technology requires development of optical coatings resistant to atomic oxygen that are durable, and that provide high performance over a large spectral range. Additionally, the behavior of coatings at low temperatures needs characterization along with the development of analytical tools necessary to support advanced coatings technology.

Advancements in *Materials Science and Engineering*, which develops, characterizes and demonstrates materials, test methods and predictive models for new materials, are required. This is particularly important to achieve dimensionally stable materials, interfaces, joints, and contact surfaces.

Required developments in *Environmental Protection* have the objective of monitoring and maintaining performance in the presence of a hostile space environment and self-contamination from the spacecraft. Development of coatings and metrology systems is required to enable the lifetimes expected by the large scale missions of next century astrophysics missions. Also required is an enlarged ground and space test program.

Required developments in *Reflector Substrates* include low areal density, high surface accuracy and smoothness, varying size, shapes, and operating temperatures. Continued development of composite materials to produce optically stable structures is recommended along with increased emphasis in lightweight material substrate fabrication technology for optics replication. Also necessary is the development of substrates for active/adaptive optics.

Developments in *Structures* technology are critical. Optical positioning structures for the next century astrophysics missions will in general be larger, lighter, and more susceptible to jitter and vibration by at least an order of magnitude of current experience. Development of these advanced

structures and the development of techniques to characterize and verify their performance in the laboratory before committing them to a mission are the principal objectives of this thrust. This includes the development of structures and mechanisms techniques that will facilitate precision erection, alignment, and control of large telescopes. Necessary will be the advancement of modeling analysis capabilities and the development of a microdynamics structure and control breadboard to allow measurements of critical parameters.

4. Optical Testing

The Optical Testing panel made development and testing recommendations in six areas: surface figure, surface roughness, alignment, image quality, radiometric quantities, and stray light suppression.

Current capabilities in testing *Surface Figure* measurements of figure quality and shape with high spatial resolution and high speed are surprisingly limited and need development. New interferometric technology must be developed that will allow for the detection and interpretation of more complicated fringe patterns to reduce the requirements placed on existing detectors and null optics. In addition, improved calibration procedures are needed to push the accuracy of these tests towards the 1 nm level from their current level of about 10–20 nm. Specifically, the testing of aspheric surfaces, large convex secondaries, cryogenic measurements, sources and detectors for optical measurements, and grazing-incidence x-ray mirrors needs development.

Surface Roughness measurements define the surface properties at smaller scales than those met by surface figure measurements. Optical profilers for cylindrical and general aspheric surfaces need to be developed. The spatial frequency of roughness measurements needs to be extended to near atomic dimensions to support development of new fabrication techniques. Also requiring development are the measurement tools that will establish the relation of subsurface damage to final achievable surface roughness.

Alignment is perhaps in the most primitive state of all the optical testing technologies. The procedures used to align complex, multimillion dollar optical systems are essentially ad hoc, with little or no model verification of the procedure before or during the alignment process. Development of partially assembled system alignment techniques is required for the assembly and test of optical systems containing large numbers of components. Segmented optics initialization development is required for phasing large segmented optical systems. The effort will be to simulate the various algorithms, the operating software, and the mirrors, including distortions, diffraction, and high- and low-frequency spatial errors to demonstrate the ability to initialize a system. Improvements in laser gauges by a factor of 10 are necessary to reach the 0.1 nm level. Developments in optical and mechanical software interactivenss are necessary to provide fast and accessible to varied users.

Image Quality measurements on partially assembled systems as well as complete systems will allow verification of system performance. Image quality metrics include: encircled energy, Strehl ratio, the optical transfer function, and quality of the transmitted wavefront. Collimated sources with the requisite wavefront flatness and radiometric uniformity must be available for many different wavelengths with development especially needed in the UV. In those cases where it is not feasible to measure the wavefront across the entire aperture, and therefore subaperture measurements will be required, improved stitching software is required to go from the sub-aperture wavefront to the full-aperture system wavefront. Additionally, improvements in diffraction analysis modeling are needed to reduce the number of measurements required and to reduce the effects of noise sources and number of misalignments.

Radiometric Quantities such as transmittance, reflectance, radiance, and polarization are difficult to measure, particularly at the outer wavelength regimes of the Astrotech mission set. Two major technology areas require development. The first is to develop

the material data bases that allow proper build designs, tested and validated. Significant tests are required of the complex refractive index and reflectivity, particularly of ultraviolet and x-ray materials. There is no empirical polarization property data base available to system designers. The necessary test of materials must be made and documented in a usable catalog. The second technology development is to increase the accuracy and capability of the measurement instruments. An order of magnitude improvement is needed in absolute radiometric calibration, polarization, and radiometric quantities.

Many of the Astrotech missions will require very good *Stray Light Suppression*. Stray light measurement is limited in dynamic range, near angle scatter and wavelength region. Space-based cleaning holds the promise of decreasing background noise on systems like the Space Infrared Telescope Facility (SIRTF) by a factor of 100. This type of return should be further developed. Bidirectional Reflectance Distribution Function (BRDF) data below wavelengths of $0.4\ \mu\text{m}$ and above $20\ \mu\text{m}$ is almost nonexistent. Funding is necessary for the enhancement of existing facilities and the fabrication of vacuum UV BRDF instruments. Then data should be accumulated on mirrors, filters, lenses, and black coatings so that stray light analyses in the future will have realistic BRDF data to work with. Funding should be provided for the development and characterization of Lambertian reference materials for the UV, IR, and far IR wavelength regions. Very near angle scatter measurements are an important part of many of the missions. None of the existing BRDF instruments measure high quality, low scatter surfaces at angles less than about $0.5\ \text{deg}$. New methods are probably needed to evaluate the BRDF at angles much less than $0.5\ \text{deg}$. Additionally, techniques need to be developed that prevent scattered light from a bright "point-like" stellar sources from reaching the detector, be it the detector of the BRDF instrument or the science sensor.

5. Optical Systems Integrated Modeling

The Optical Systems Integrated Modeling panel identified four critical areas for further development: integrated package for initial design, interface development for detailed optimization, validation, and modeling research.

An Integrated Package for Initial Design addresses the need for a high level optimization tool. Accessible software tools are needed that allow initial designs to be characterized quickly and inexpensively. The characterization must include the system's response to dynamic and thermal perturbations as well as static performance. These tools must also be capable of providing an early and reasonably accurate understanding of the expected imaging and radiometric performance of the system.

Interface Development for Detailed Optimization addresses modeling for detailed system and subsystem optimization. Existing software is available to carry out major portions of the modeling effort, but these components of software are generally separate dedicated packages that address the geometrical design, physical optics analysis, structural analysis, and thermal effects separately. Since future missions will be dominated by the size and complexity of the optics, these separate areas must be tied together to permit system-level evaluation of future design concepts. Integration of existing software and the development of advanced codes are required to enable end-to-end system performance evaluation. This includes the development of an integrated modeling computer program for initial design of large and complex advanced space optical systems.

Also critical to integrated modeling is *Validation*. All modeling software must be validated as part of the development effort. Software that cannot produce experimentally corroborated answers is useless. Additionally, since most of the advanced

modeling capabilities required are very limited or non-existent, validation with experimental demonstrations or hardware has not occurred and is necessary.

Modeling Research is recommended for development. While most concepts covering optical propagation are well founded, there are some critical areas that need basic development for incorporation into an integrated modeling process. Additional research and development into specific types of models (diffraction, scattered light, image inversion) and modeling techniques is required to improve model performance, relevancy, and clarity to a broad technical community.

6. Advanced Optical Instruments Technology

Six technologies that need to be developed in Advanced Optical Instruments are directly related to specific scientific measurements: gratings, tunable filters, interferometer beam combiners, optical components, starlight suppression, and fibers.

Gratings are needed with improved diffraction efficiency, particularly in the UV. Reduced scatter at all wavelengths is required to increase measurement signal-to-noise ratio. Aspheric, x-ray, and holographic blazed gratings of large size are also required to support the instrument concepts of the Astrotech mission set.

Tunable Filters encompass acousto-optic tunable filters (AOTF), Piezoelectric-tuned Fabry-Perot filters, and birefringent filters. These filters need further development for detecting the velocity distribution of extended emission line objects by looking at the spectral shifts of their emission lines in the UV, visible, and near IR.

Interferometer Beam Combiners, necessary for the new emerging scientific instruments called interferometers, exist in a number of forms: pair-wise pupil combiners, n-wise pupil combiners, and image plane combiners. The only developed beam combiner is the pair-wise pupil combiner. All of the others are required for the large scale multiple aperture interferometric measurements of future missions.

Optical Component technology is essential for the continued development of science instruments. The Advanced Optical Instruments group identified a number of components required for new science measurement capabilities. These include x-ray and ultraviolet windows, grids and gratings, binary optical elements, narrow band filters, tunable filters and advanced fiber optic systems.

The *Stray Light Suppression* effort focuses on the development of coronagraphs, nulling interferometers, and Woods filters. The coronagraph and nulling interferometer development would advance suppression levels to 10^{-4} – 10^{-6} for the visible and UV regimes. Suppression in the IR at 10^{-4} levels would also be developed.

The *High Potential Fiber* development program will focus on advancing fiber technology. The initial phase of the development will address the characterization of fiber materials (e.g., polarization, attenuation, dispersion, transmittance, etc.) applicable to the IR and UV regimes. Research will also concentrate on new and advanced materials and the fabrication processes necessary for fiber development.

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SECTION I ASTROTECH 21 PROGRAM OVERVIEW

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Space astronomy is about to embark on a period of great discovery. During the 1990s, four great observatories will be launched to probe the universe in spectral regions ranging from gamma radiation to the far infrared. But NASA is already looking beyond the Great Observatories to even more challenging missions to be launched during the first few decades of the next century. New technology advances that enable observations with higher angular resolution, greater sensitivity, and the exploration of new spectral regions are viewed as vital for continued scientific progress. In 1989, the NASA Office of Space Science and Applications Astrophysics Division in cooperation with the NASA Office of Aeronautics, Exploration, and Technology created Astrotech 21 to devise a technology development plan for the astrophysics missions for the 21st century. The resulting plan was developed through three series of workshops that had different, yet related, goals.

The first series consisted of three workshops that addressed the science objectives and architectures for future missions in the disciplines of High Energy Astrophysics, Optical Interferometry, and Submillimeter Interferometry. In these forums, scientists and engineers met to discuss the astrophysical phenomena that could be observed with enhanced observation capabilities, the performance measurements required for these observations, and the various possible observatory architectures.

After developing science objectives and architectures for the New Century Astronomy Program in the first workshop series, a second series was held to better develop the mission concepts and identify specific technology requirements. Four such workshops were held and attended by participants involved in point mission design studies in the areas of: optical interferometry, laser gravitational wave observatories, advanced orbiting very long baseline interferometry (OVLBI), and large filled-aperture telescopes.

To synthesize the disparate technology requirements from the Astrotech 21 mission set in a coherent fashion, a third series of three integrated technology planning workshops were held concerning the critical areas of information systems, sensors, and optics. The goal of these workshops was to evaluate the new requirements in the context of existing and projected capabilities, and to recommend technology development programs whose justifications are directly traceable to the science goals of the mission set. This Proceedings publication summarizes the analyses and recommendations of the workshop on optics technology.

The proceedings of each workshop have been documented in separate volumes of this series; the final volume integrates all workshops and planning activities into a single technology development program plan for future space astrophysics missions.

